Sand in motion

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6 Cross-shore sorting according to grain size and density

Not only the distribution of sediments along a coastal profile is topic of study in literature, also the response of a sediment distribution on changing morphology has been investigated previously, mainly in the framework of offshore sediment nourishments. The experiment described in this chapter focuses on the distribution of grain size and density on a cross-shore profile. Therefore, two new techniques to measure grain size *in situ* are used and validated. These techniques can give distributions of sediment composition faster and with a higher spatial resolution that the traditional sediment sampling. The heavy-mineral concentration is also measured with the MEDUSA system.

Although the profile only changed slightly at the end of the experiments, sediment composition keeps changing until the end of the experiments with storm conditions. This indicates that the presence of a morphological equilibrium does not necessarily indicate that also sediment composition is in equilibrium. The equilibrium distribution of grain size, "lags" behind morphologic equilibrium.

6.1 General

The experiments in the Large Wave Flume (LWF) in Hannover, Germany were part of the EU MAST-III-programme SAFE. The main goal of these experiments was to study morphological evolution of a coastal profile under erosive storm conditions, with and without structural dune protection with normal beach sand (Newe *et al.*, 1999; Peters and Dette, 1999). The experiments described in this thesis have been run as part of this programme.

Most of the experiments were a combination of hydraulic conditions comparable to fair weather waves and water level (h=4.0 m, H_{mo}=0.65 m, T_m=5.5 s), and waves and water level conditions comparable to a storm surge (h=5 m, H_{mo}=1.2 m, T_m=5.5 s). In between experiments, a shovel flattened the large-scale morphological structures, but no special attention was paid to redistribute the upper layer of the sediments over the profile. This implies that the sediment distribution at the start of an experiment already represents more or less an equilibrium response (Horn, 1992) to the overall hydrodynamic conditions of the previous experiments. The changes in sediment composition within one experiment are therefore expected to be small, but the final distribution of the sediment texture will give insight in the sediment sorting processes on the profile under the specific conditions.

The median grain size of the sediment has been determined from activity concentrations and friction sound, measured with the MEDUSA system. These signals not only reflect independent quantities but the sensors have also been calibrated separately. The intercomparison of the two types of results and the comparison with median grain size from sediment samples from the final profile will be used to discuss the possibilities of these new techniques and to validate the techniques to determine grain-size distributions *in situ*. The measurements with the MEDUSA system give the opportunity to determine sediment composition in between the runs while water is still present in the flume. Therefore a time series can be constructed that gives an overview of the adaptation time of a grain-size distribution.

The focus of the experiments has been on morphological evolution of a coastal system with an initial slope of 1:20 under erosive storm conditions (Newe *et al.*, 1999). In this thesis two experiments are described: experiment GA, denoted as series D in Dette *et al.* (1998) and experiment GB, denoted as series E in Dette *et al.* (1998). In experiment GA a high barrier of big bags protected the dune, in experiment GB, the barrier of big bags has been lowered, such that only the lower part of the dune was protected.

The experiments in the Scheldt flume focussed on density sorting. In the LWF experiments a coupling will be made between the sorting on size and density at a scale similar to that in nature.

6.2 Results

6.2.1 Profile development and sediment transport

The profile evolution and volumetric sediment-transport rates inferred from the profile changes (see (5.1)) of two time intervals of experiment GB are presented in Figure 6.1. The morphology of the profiles shows clearly how a breaker bar develops between x=210 and x=230 m. On the onshore and offshore side of the breaker bar, changes in profile are small.

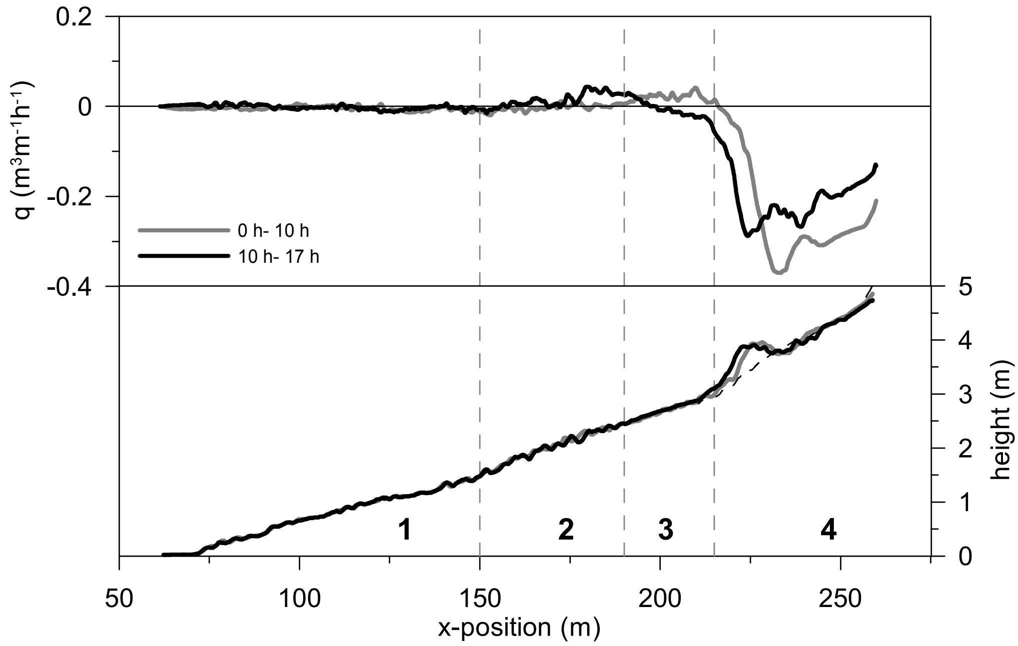

Figure 6.1: Profile development and total sediment-transport rates for 2 time intervals of series GB. The numbers point to the four morphological units described in the text.

The small-scale morphology of the first and final profile for the profile between 100 and 210 m is presented in Figure 6.2. These results show that the initial profile is not completely smooth, but small morphological variations are present. In the region 100<x<150 m (region 1) during the run, the sedimentary structures develop. These structures are mainly small-sized wave ripples with ripple length $\lambda = \sim 1.5$ m and ripple height $\eta = 0.05\text{-}0.10$ m. In zone 2 (150<x<190 m) ripple structures are larger. The shape of the ripple structures is slightly asymmetrical, pointing to an onshore-directed ripple migration. In the region just seaward of the breaker bar (zone 3), ripple structures are absent on the final profile. The three zones reflect a transition from an immobile bed due to low flow conditions in region 1 towards ripple structures due to an increased flow as a result from wave shoaling in region 2. For increasing flow conditions, ripple structures flatten and sheet-flow processes will result in a plane bed (region 3).

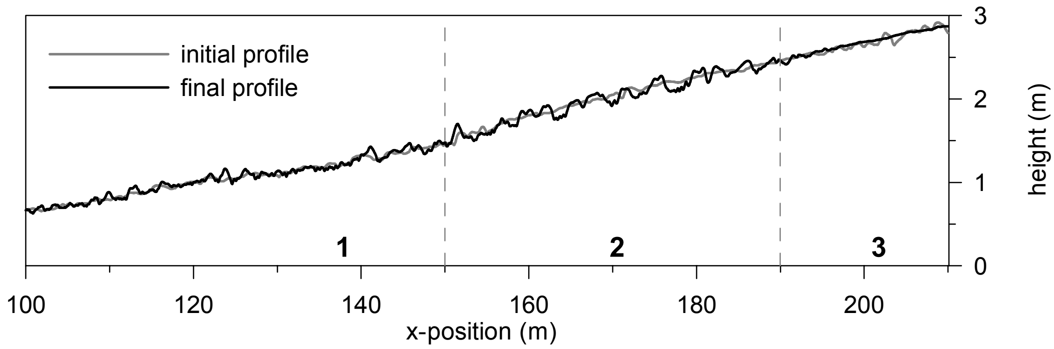

Figure 6.2: Close-up of the ripple structures for the first and final profile of experiment GB in the region 100<x<210 m. The numbers point to three of the four morphological units described in the text.

Visual observation on the sedimentological structures show that the breaker bar in region 4 lies as a blanket over the more offshore located sediments, analogous to an offshore migrating turbidity current (Walker and James, 1992).

The sediment-transport rates in Figure 6.1 show that small fluctuations around zero occur for x<215 m; for x>215 m transport rates become much larger and negative. At the waterline (x=260 m) sediment-transport rates are still smaller than zero, indicating erosion of sediments. One of the requirements of the volumetric sediment transport calculations is the total conservation of the sediment volume, which means that sediment-transport rates on both ends of the profile should be equal to zero. The results in Figure 6.1 show that this is not the case.

The experiments were constructed with a structural protection of big bags in front of the dune. This barrier had a height such that waves could easily overtop the barrier and erode sediments from the dune (Dette *et al*., 1998). In the profile measurements, the dune area could not be measured and the total measured volume of sediments in the flume increased with time. This causes the non-closure of sediment-transport rates at the beach face.

The differences in small and large-scale morphology show that the profile can be divided in four morphological units marked by differences in sediment-transport rates and distinct morphological properties:

1) *Lower shoreface (100<m<150 m)*
   On the lower shoreface sediment-transport rates indicate that there is no net transport of sediments throughout the entire experiment. Morphology shows the development of small-scale ripple structures, but changes are only small.
2) *Outer surf zone (150 <x<190 m)*
   In the outer surf zone, sediment-transport rates are equal to zero in the first half of the experiment and are, although small, directed onshore during the second part of the test. Morphology shows the appearance of slightly asymmetrical ripple structures with $\lambda = \sim 3.5$ m and $\eta = 0.2$ m. These structures disappear in onshore direction. This transition of ripple structures to a plane bed for 185<x<195 m, shows a decrease of ripple height, but ripple length is more or less equal.
3) *The outer surf zone just offshore of the breaker bar (190<m<215m)*
   The profile in this region becomes more or less smooth during the experiment. The net sediment-transport rates in the first time interval are small and directed onshore. In the second time interval, net transport rates are still small but become offshore directed. The fact that there is hardly any net sediment transport, does not imply that sediments are not moved in this area. On the contrary, the total amount of mobilised sediment can be very large, but due to the nature of the flow, the total volume of sediments shows no net displacement. The flat morphology in this region represents upper stage plane bed and is the result of sheet-flow processes.
4) *The inner surf zone (x>215 m)*
   In the inner surf zone, sediment-transport rates are directed offshore for both time intervals, and decrease with time. The morphology shows the development of a breaker bar around x=225 m, but with little erosion in the trough area (230<x<250 m). Most of the sediments that built the breaker bar originate from the (unmeasured) dune erosion. These results corroborate the visual observation that the breaker bar moves offshore as a blanket covering more offshore sediments.

6.2.2 Validation of grain-size measurements

In the experiments, grain sizes of the sediment bed are determined by three methods: sieving sediment samples, radiometry and friction sound. Sediments are sampled by locally scooping of a thin (2 cm) layer with a spade. These samples represent only point locations. Visual observations on the bed forms indicated that grain sizes vary considerably over ripple structures. The measurements with MEDUSA are global and give an average value over a certain area. Radiometric measurements have been averaged over a length of 8 m, the friction-sound measurements are sampled at 0.5 m intervals. Besides a difference in spatial resolution, the three methods provide also information over different depth ranges. Sediment samples were taken from a depth up to ~2 cm, the measurements of γ-ray activity with MEDUSA give activity concentrations averaged over a depth of about 20 cm and the friction-sound measurements are likely representing the upper few millimetres.

Since the friction-sound measurements do not (yet) provide calibrated values, friction sound is calibrated in the flume. To that end, the sound intensities measured on the locations of sediment samples are correlated to the median grain size of the sediment (see chapter 4). This correlation has been used to calculate the median grain size from the sound intensities. The radiometric measurements of MEDUSA give calibrated results of the radiometric properties of the sediment. The correlation between grain size and radiometry is subsequently determined in the laboratory from several sediment samples. The conversion of the radiometric signal to median grain size is therefore independent of the locations of the sediment samples.

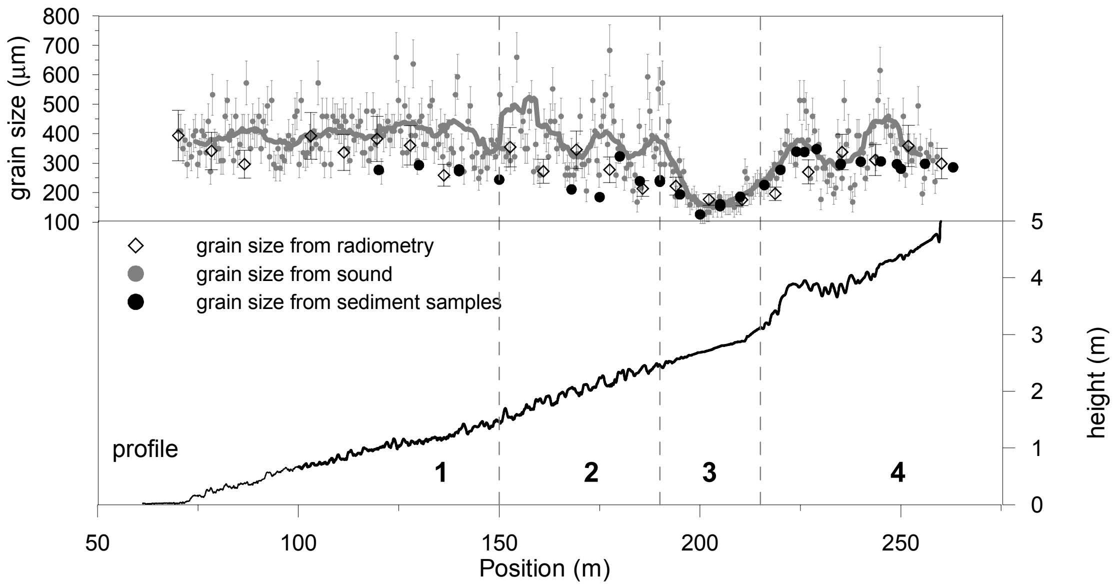

Figure 6.3: Grain-size distribution along the profile, obtained from radiometric measurements, from friction sound and sediment samples. The grey line represents a running average trough the friction-sound grain sizes.

The median grain-size distributions measured along the final profile of experiment GB, are presented for the three methods in Figure 6.3. These results show a considerable similarity of the large-scale distribution of the grain sizes and are indicative of the reproducibility of the different techniques. In the region for 50<x<190 m (region 1 and 2), grain-size determinations from radiometry and friction sound are similar. The sound signal shows more variation likely due to the higher spatial resolution of the friction-sound measurements. The scatter in the sound measurements may represent grain-size variations on a small spatial scale, e.g. due to sorting on small ripple structures. Compared to the sediment samples, the grain size from friction sound is on average 40% larger. It appears that the sediment samples correspond to the smallest grain sizes determined from the friction sound. The exact reason for this discrepancy is not known, but we hypothesize that it is the result of differences in vertical resolution and of the time-span between friction-sound measurements en sediment sampling. The friction sound and MEDUSA measurements were recorded just after the experiments. The sediment could only be sampled after the water was drained from the flume slowly to prevent flattening of ripple structures. Consequently, the finest sediments (wash load) could settle, mainly in the troughs of the ripple structures. To avoid biasing of fine material in the sediment samples, samples have mainly been (selectively) collected from the sides of the ripple structures. Although this selective sampling avoided the contamination with fines, it is well possible that coarser sediments, that are often located in the trough, are not collected. Moreover, in a region with small sediment-transport rates, coarse materials are often locating in the upper layer of the sediment. Since the friction-sound level is most sensitive to the upper layer, we can expect that measured grain sizes are larger than sizes from sediment samples. These results indicate that the upper layer of the sediment is coarser than the underlying sediments.

In region 3, all measurements give similar results. For region 4, most measurements are equal, but the grain sizes determined from friction sound seem to be larger than the radiometrically determined samples around x=230 m

These results indicate that the values of the *in situ* measurements of grain size with respect to the traditional, time consuming, sediment sampling and sieving are not only comparable, but also yield more detailed and complementary information.

6.2.3 Distribution of grain-size classes

The measurements with MEDUSA in the present experiments give only information on the median grain size of the sediment; the analyses of the sediment samples also give information on the grain-size distribution. Although the median grain size is descriptive of the coarsening and fining of the bed, it does not give information on the selective transport of various grain-size classes (Medina *et al.*, 1994).

The sediment samples from experiment GB are split in three size classes (0.063 –0.104 mm, 0.104-0.25 mm and 0.25-1 mm) and the results are plotted in Figure 6.4. At the start of the experiments, the sediments are distributed homogeneously along the profile. The grain size distributions in Figure 6.4 represent the distribution after two experiments with equal wave conditions. The finest grain-size fraction shows up in only very small concentrations for x<190 m (region 1 and 2) and increases in region 3. The maximum concentration of the fine fraction (~50%) is found in the centre of this region (x=200), characterised by a flat morphology. For x>200 m the percentage of the fine fraction decreases again and is almost absent for x>215 m (region 4).

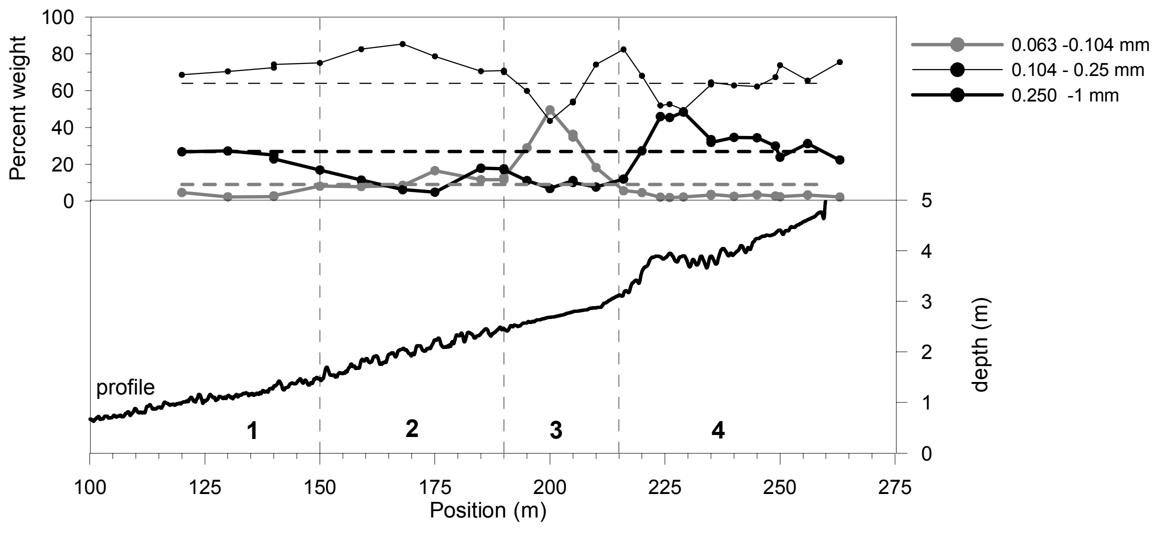

Figure 6.4: Distribution curves of three grain-size classes at the start of the experiment (dashed line), the distribution of grain-size classes at the end of the experiment (solid lines) and the corresponding final profile of experiment GB.

The contribution of the median grain-size fraction (0.104-0.25 mm) increases slightly from x=110 m to x=165 m. From this location onwards, the contribution of the medium-sized fraction remains in general constant except for two minima around x=200 m and x=225 m. The minima coincide with maxima in the fine and coarse fraction respectively. The largest grain-size fraction (0.25-1 mm) has a contribution to the total sediment of ~20% at x=125 m. This decreases in onshore direction until <5% at x=175 m and increases from there in shoreward direction. The maximum value of ~50% is reached at x=225 m, the position of the breaker bar.

Summarised, the distribution patterns of the three grain-size classes indicate a subtle onshore fining of sediments on the lower shoreface (region 1) and part of the outer surf zone (region 2). In the most onshore side of region 2, close to the transition of rippled morphology to the flat bed of region 3, the contribution of the coarsest fraction is as large as the original contribution and decreases again for x>200 m. The region of flat bed (region 3) is characterised by the increase of the finest grain-size fraction. The relative contribution of the coarsest fraction is more or less constant but smaller than the original contribution; the relative contribution of the medium-sized fraction decreases. On the transition of region 3 and region 4, on the seaward side of the breaker bar, the contribution of the medium sized fraction is increased. In the inner surf zone and breaker bar (region 4), the fine fraction is almost absent; the coarse fraction is increased with respect to the initial distribution.

These results show that the sediments do not behave as a bulk sediment fraction, but the variations of the median grain size (Figure 6.3) is the result of variations that can be described by three grain-size classes.

6.2.4 Sorting on density and grain size

The measurements of natural radioactivity were not only used to derive the median grain size of the sediment, but also to determine (small) heavy-mineral concentrations that were originally present in the sediment. The distributions of median grain size and heavy-mineral concentration from the radiometric measurements of the final run are presented in Figure 6.5. In the comparison of the final and initial sediment distribution we assume that the sediments are initially homogeneously distributed. These results show that the heavy-mineral concentration is generally very low (< 3.5%), but that significant variations occur.

On the lower shoreface and outer surf zone (regions 1 and 2) the heavy-mineral concentration is, similar to the median grain size, more or less constant. The average heavy-mineral concentration of 1.7% represents the characteristics of the original sediment. The radiometric measured median grain size decreases slightly in shoreward direction. In the outer surf zone just offshore the breaker bar (region 3) the median grain size is smallest, but the heavy-mineral concentration shows a maximum of 3.5 % at x=190 m. On the breaker bar (215<x<235 m) the median grain size increases in landward direction to a maximum in the inner surf zone. The median grain size in region 4 is similar to the values on the lower shoreface. The heavy-mineral concentration is constant in entire region 4, and has a concentration similar to the original sediments on the lower shoreface.

Variations in median grain size can be observed along almost the entire profile, except for the lower shoreface. At this location, the median grain size is constant. In contrast, the heavy-mineral concentration differs only from the original sediments in region 3, the region offshore the breaker bar, where sheet-flow conditions are met.

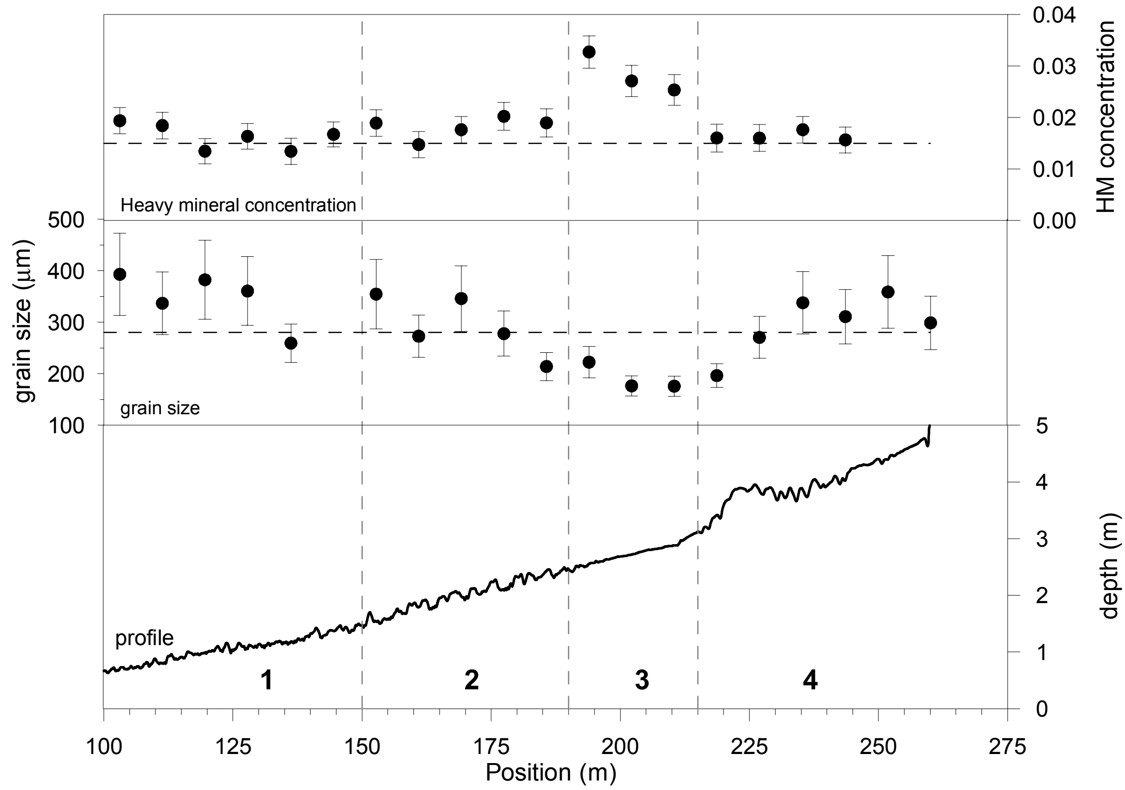

Figure 6.5: Distribution of grain size and heavy-mineral concentration (by weight) measured with radiometry over the final profile of the experiment with storm conditions and dune protection (GB). The dashed horizontal lines represent the initial sediment distribution.

6.2.5 Differences in hydrodynamic conditions and sediment sorting

Sediment distributions are the result of an interaction between hydrodynamics and morphology and are often thought to represent an equilibrium distribution, in response to the specific conditions. How fast sediments are redistributed under changing hydrodynamic conditions is still questioned.

For series GA, with a slope of 1:20 and a high barrier in front of the dune, the hydrodynamic conditions have been changed during the experiment. This experiment started from the initial plane bed with sediment that was not already distributed by previous experiments. The first 16 hours of the series consisted of storm conditions (H_{m0}=1.2 m, T=5 s); in the last part of the series the water level was lowered by 1 m and for 7.5 hours the profile has been exposed to fair-weather conditions (H_{m0}=0.65 m, T=5 s). The time-averaged sediment-transport rates of the fair weather and storm conditions together with their two final profiles are presented in Figure 6.6. These results show that during both conditions, sediment-transport rates are negligible in region 1 and region 2. The sediment-transport rates in region 3 are negligible for the fair-weather conditions, but during storm conditions, a small onshore sediment transport can be observed. These transport rates are small and have no clear effect on morphology. For the most onshore region (zone 4), the sediment-transport rates become offshore directed and have a maximum for 230<x<245 m. From here on the sediment-transport rates decrease in onshore direction. The offshore directed sediment-transport rates result in erosion from the inner surf zone and a deposition of sediment on the breaker bar, located at 220<x<235 m.

In the experiments with fair weather the sediment-transport rates in the inner surf zone show a different behaviour: for 220<x<230 m the sediment-transport rates are directed in offshore direction, at a magnitude similar to the sediment-transport rates of the storm conditions. Sediment-transport rates are onshore directed for 230<x<265 m (in the region above mean water level), resulting in a flattening of the storm-surge breaker bar.

As described in section 6.2.1, sediment-transport rates should be equal to zero at the beach when the total volume of sediment is conserved. The results in Figure 6.6 show that the sediment-transport rates near the beach are close to zero and indicate that the total volume of sediment (including pores) in the flume is conserved.

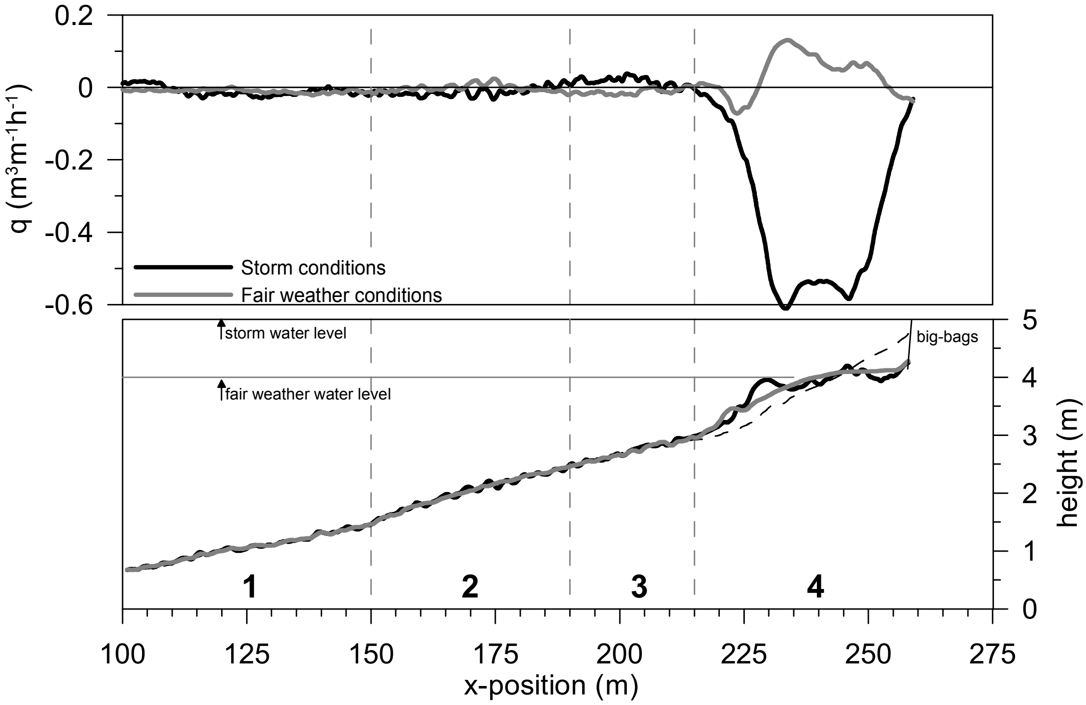

Figure 6.6: Time-averaged sediment-transport rates and final profile of experiment GA under storm and fair-weather conditions. A positive sediment transport rate is onshore directed.

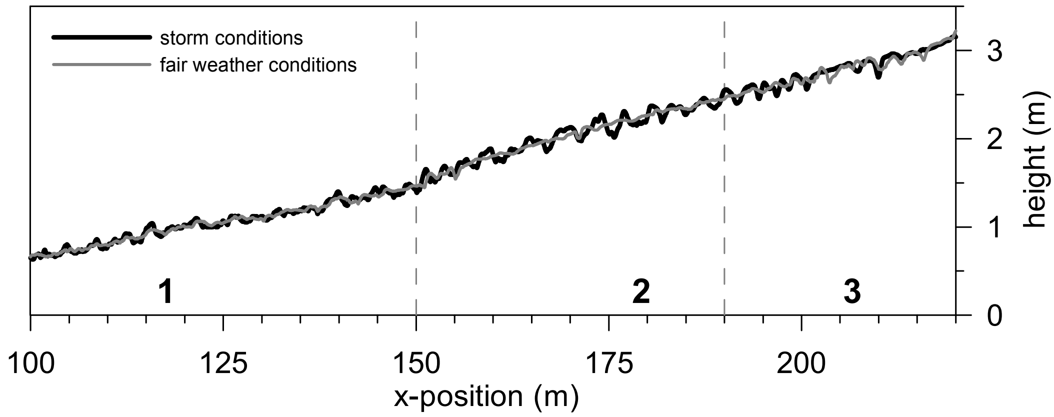

Figure 6.7: Close up of the profile after storm and fair-weather conditions of experiment GA.

For a comparison of the detailed morphology between storm and fair-weather conditions and to study the difference between the storm conditions of experiment GA and experiment GB (see section 6.2.1), a close up of the profile is presented in Figure 6.7. These results show that the ripple structures in region 1 are small and are independent of the conditions. The ripple structures developed during storm conditions but probably remained as relict structures during fair-weather conditions. During storm conditions, the ripple structures in region 2 increase with respect to the ripple structures in region 1.

During fair-weather conditions (second part of experiment GA), the ripple structures in this region are flattened. In contrast to the measurements in experiment GB, the bed is not flat in the entire region 3 during storm conditions of experiment GA. For 190<x<200 m, ripple structures are still present. For 200<x<215 m, morphology shows some undulations but is much flatter compared to region 2. Apparently, the change from ripple regime to sheet-flow conditions occurs around x=200 m for the storm conditions of experiment GA and also the change of region 2 to region 3 should be located at x=200 m. The difference in the location of the region of flat bed for the storm condition of experiment GA and experiment GB can be explained by the differences in dune protection, large-scale morphology and variations in reflection of waves on the dune. In series GA, less sediment was eroded from the dune area and consequently, the breaker bar was smaller. These changes alter the hydrodynamics and will affect the location of the transition from ripple to sheet-flow regime. For reasons of consistency, the zonation is kept similar to the zonation used in series GB.

During the fair-weather conditions of experiment GA, ripple structures appear in region 3. The average characteristics of these ripple structures are: $\lambda \sim 3$ m $\eta \sim 0.1$ m.

The time variation of the grain-size distribution of the storm and fair-weather conditions of experiment GB is presented in Figure 6.8. The colour zonation represents different classes of median grain size of the sediment and thin lines represent contour lines of profile-height.

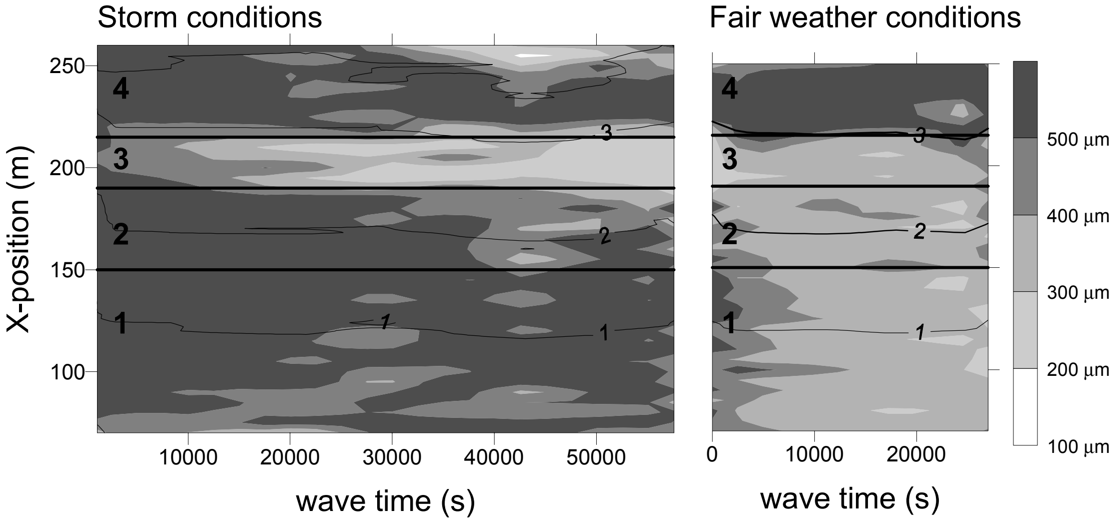

Figure 6.8: Interpolated grain-size distribution along the profile from sound intensity for the two experiments of series GA. The left-hand side of the picture shows the variation in grain size during storm conditions, the right-hand side shows grain-size variations during fair-weather conditions. The thin black lines represent the morphological contour lines, the thick black lines represent the subdivisions of the four regions.

The initial median grain size is uniformly distributed along the profile. Already after a short time period (within 10000 s) the sediments become finer up to 200-300 μm in the outer surf zone just offshore the breaker bar (region 3). The fining continues until the end of the experiment (5×10^4 s, or approximately 13h). In time, the landward border of this area with finer sediment remains at the same position, but the seaward border moves in offshore direction. Whether this is a result of the removal of coarse material or a deposition of fines is not clear.

The median grain size in the inner surf zone (region 4) is constant during storm conditions, but a rapid fining occurs around t=40000 s. This rapid decrease in grain size close to the beach is an artefact initiated by one of the big bags, used as dune protection, falling off the protection cliff. Already prior to the drop of the big bag, fine-grained material moves from the dune and undermines the protection. This can also be seen from morphological changes in this area. According to the results in Figure 6.8, the release of fine material started already around 35000 s. The fine material is redistributed soon, leaving coarse sediments as lag deposit. Simultaneously with the increase in fines in zone 4, it appears that also in zone 2, median grain size are smaller for a short time period. Apparently, the fine materials released from the cliff are redistributed up to the outer surf zone. The morphology in region 4, changed due to the release of sediment, but returned to its state prior to the release of the sediment.

For the fair-weather conditions, the water level is lowered to 4 m. Consequently, part of the inner surf zone is located above the water level and hence measurements of friction sound cannot be used for comparison. The underwater part of the inner surf zone (region 4) shows no changes in median grain size. During the initial part of the experiment, the median grain-size distribution results from the storm conditions is averaged out. This results in a rapid increase in median grain size to values between 300 and 400 μm in the outer surf zone just seaward of the breaker bar (region 3). Afterwards, the d_{50} remains similar until about the end of the experiment, when the values range between 400-500 μm. In the outer surf zone and lower shoreface, the upper layer of the sediment becomes finer (d_{50}<300 μm) in the first time period and remains constant afterwards.

In conclusion, the grain-size distribution during storm conditions clearly shows how the median grain size remains coarse in the inner surf zone (region 4) and becomes finer in the region just offshore the breaker bar (region 3). At more offshore locations the changes are small and probably related to sudden events (the drop of a big bag) elsewhere on the profile. During fair-weather conditions, the distribution of sediments in the inner surf zone (region 4) is similar to storm conditions, but differs for the other regions. The outer surf zone just offshore the breaker bar shows a general coarsening, whilst the regions more offshore shows a fining of the upper layer of sediment. The drop of the big bag could have been noticed in advance by the dispersal of the fine material. These fine sediments redistribute fast over almost the entire flume, but eventually, the original grain-size distribution is restored.

6.3 Assessment and conclusions

6.3.1 Laboratory measurements

The grain- size distribution along the profile is the result of sediment-transport processes in a specific area. The results on morphological change show how the profile can be divided in four morphological units. The difference in sediment composition and sediment-transport rates in these regions is used to define characteristic sorting processes, schematically presented in Figure 6.9.

1) *The lower shoreface*

   This region is characterised by a morphological inactive profile. The ripple structures that are present in the final profile are not different from the ripple structures present initially and sediment-transport rates are negligible.

   During storm conditions, the median grain size of the bed is more or less constant; the heavy-mineral concentration is also constant and corresponds to the initial bed composition. Under fair-weather conditions, the sediments show a fining in time.

Since net sediment-transport rates are negligible, it seems that the fining is the result of a covering by a (thin) blanket of fine sediments that hardly contributes to the net sediment transport. These fine sediments originate from a more onshore source and are probably transported as suspended load offshore.

2) *The outer surf zone characterised by ripple structures*
This part of the outer surf zone is characterised by the occurrence of ripple structures during storm conditions. These ripple structures become smaller in height and migrate in onshore direction. The median grain size shows an onshore fining. The heavy-mineral concentration is constant and has values similar to the initial heavy-mineral concentration. The sediment-transport rates during storm conditions at the most seaward side of this region are not significant, but the transport rates increase shoreward, resulting in small onshore-directed sediment-transport rates.

The results from the three grain-size measurements (friction sound, sampling and radiometry) indicate that the upper layer of the sediments is coarser than the sediments below. Since sediments transport processes occur in the upper active layer, it is tentative to conclude that sediments coarsen in time, which is probably the result of the selective removal of fines.

The changes in ripple height and onshore increasing sediment-transport rates are indicative for increasing hydrodynamic conditions due to wave shoaling. Wave shoaling results in an onshore-directed asymmetrical water motion and is known for its capacity of sediment sorting (de Meijer *et al.*, 2000; Dohmen-Janssen, 1999; Tánczos, 1996). In this region, the flow is only effective in the sorting based on size, since the heavy-mineral concentration is constant.

The sudden change in median grain size in the experiment, where a part of the dune protection failed (Figure 6.8), shows how the release of fine-grained material from the inner surf zone influences the sediment composition in this area. Apparently, (catastrophic) processes other than asymmetrical wave motion can also influence this region, but the sorting by asymmetrical wave motion prevails and sediments are redistributed soon after the release of fine-grained material.

3) *The outer surf zone just offshore the breaker bar*
The morphology of this area is characterised by a plane bed during under storm conditions and of ripple structures under fair-weather conditions. Net sediment-transport rates in this region are not significant in experiment GB, but are small and onshore directed during the storm conditions of experiment GA. Although the conditions for both experiments are equal, the local hydraulic conditions can differ due to variations in morphology. In experiment GA, less sediment was eroded from the dune area and consequently, the breaker bar was smaller. The resulting differences in hydrodynamics can explain why sediment-transport rates and small-scale morphology (ripple structures and plane bed) differ in experiment GA and GB for this region. During the fair-weather conditions, net sediment-transport rates are not significant.

The decrease in median grain size shows up as an increased concentration of the fine fraction. The heavy-mineral concentration is higher than in the original sediments. The largest concentrations are found on the most seaward side of this region.

Although the net sediment-transport rates are small, sorting of sediment occurs. Also under sheet-flow conditions, the asymmetry in the oscillating flow is responsible for the sorting of sediments on size and density. The more dense heavy-minerals have lower net onshore-directed sediment-transport rates (Tánczos, 1996) than quartz and are concentrated at the shoreward side of the region.

The coarsening of the sediments during fair-weather conditions occurs without significant sediment-transport rates. Whether the coarsening is the result of removal of fines or the deposition of coarse material is not clear, but the fact that a small amount of fine-grained material is deposited more offshore (region 1) points to segregation of sediments on grain size. This segregation can be the result of selective sediment-transport processes due to asymmetrical wave motion (see e.g. Tánczos, 1996).

4) *The inner surf zone*
During storm conditions, the inner surf zone is characterised by large net offshore sediment-transport rates and a coarsening of the bed. Sediments eroded from the dune are redistributed fast, leaving sediment with a grain size similar to the original state. This redistribution seems to be a continuous process. The general erosion of this area and the result that the bed coarsens indicates that the coarse material is concentrated as a lag deposit.

Visual observations on the profile revealed that the breaker bar progrades offshore analogue to a turbidity current (Walker and James, 1992): the breaker-bar sediments are deposited as a blanket over the poorer sorted sediments located more offshore. This indicates that the sediments eroded from the dune and trough area are transported offshore, probably by the undertow. These sediments are sorted during deposition by their settling velocities and build the breaker bar. The distribution of the three size classes (Figure 6.4) corroborates this hypothesis: coarse material is found on the most seaward side of the breaker bar; the medium-sized class is deposited more offshore. Due to the erosion in the trough, coarse lag deposits are found in the upper layer of the sediment.

Under fair-weather conditions, the breaker bar is flattened by offshore directed sediment transport on the seaward side of the breaker bar and onshore directed sediment-transport rates on the landward side of the breaker bar. The median grain size does not change and it is not clear whether sediment transport is selective on grain size.

The experiments of the storm conditions lasted until an "equilibrium" profile had been developed and total sediment-transport rates decreased to a minimum (Newe *et al.*, 1999). Although the profile only changes slightly at the equilibrium condition, the sediment composition keeps changing until the end of the experiment, especially in the region of fine grain sizes (region 3). Apparently, the presence of a morphological equilibrium does not necessarily indicate that also sediment composition is in equilibrium. These results indicate that the equilibrium distribution of grain size "lags" behind in time compared with a morphologic equilibrium.

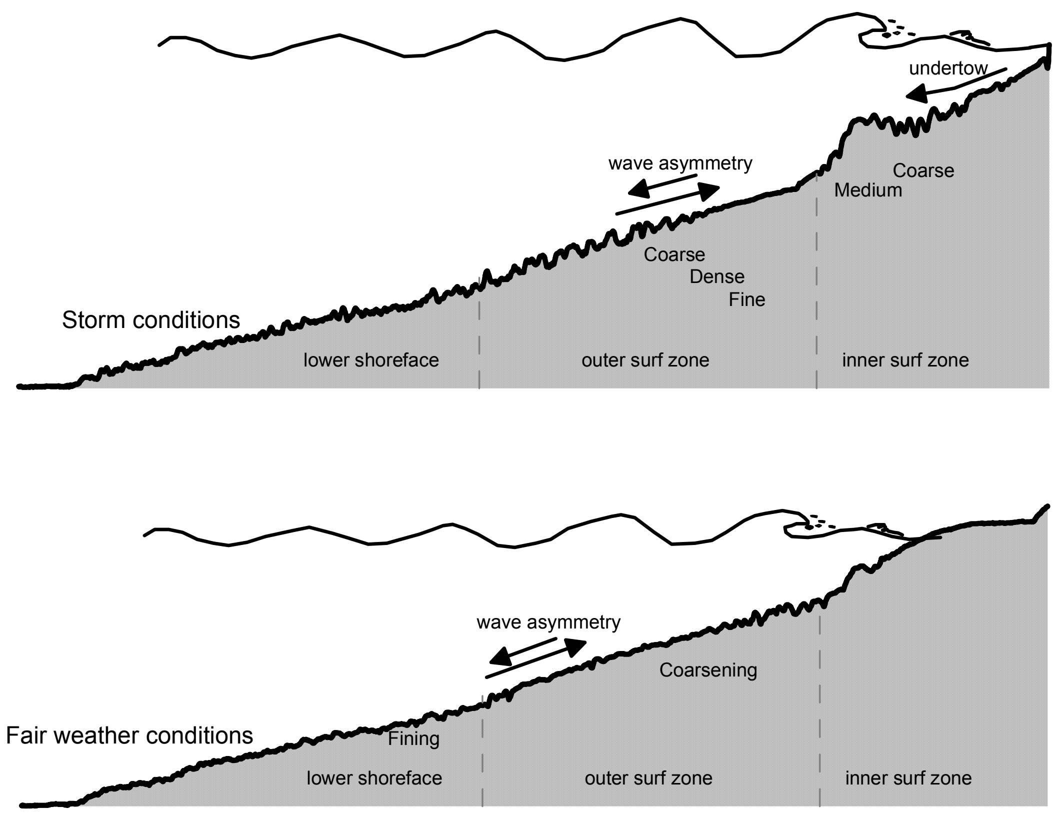

Figure 6.9: Schematisation of important sediment transport modes responsible for sorting of the size fractions during storm and fair-weather conditions observed in the experiments.

6.3.2 Comparison with field measurements

Previous studies on the sorting of sediments with respect to profile evolution have mainly taken place in the field (Guillén and Hoekstra, 1996; Liu, 1989; Stauble and Bass, 1999; Terwindt, 1962).

These results lead to classifications similar to the classification of the present experiments. Guillén and Hoekstra (1996) based such a classification on the distribution of sediments on a coastal profile off the coast of Terschelling, The Netherlands, and coupled these classes to differences in adaptation periods. They described the lower shoreface and outer surf zone, characterised by an offshore increase of the median grain size, as a low-mobility zone. The offshore increase of coarse material has been observed in laboratory experiments of Zhang *et al.* (1996) but also in other field measurements (see e.g. Liu, 1989) and is a phenomenon generally attributed to the selective removal of fines in shoreward direction.

Also the flat bed of the outer surf zone just offshore the breaker bar is observed in the field measurements of Guillén and Hoekstra (1996). The grain size in this region is constant and the transition of the flat-bed region to the low-mobility zone is described as the 10-years averaged closure depth. The closure depth is defined as a depth where the net cross-shore sediment-transport rates are so small, that changes in morphology become not significant (Hallermeier, 1977; Hallermeier, 1981a; Nicholls *et al.*, 1998). Other field measurements (Stauble and Bass, 1999) also showed the presence of a region of coarse-grained material located at the 10-years averaged closure depth. Apparently, the location of initiation of sorting on grain size represents a depth that is critical for intense reworking of sediments. A more elaborate discussion on the depth of closure and sorting of sediments will be given in chapter 8.

The shallowest region is classified as a high-mobility zone (Guillén and Hoekstra, 1996), characterised by a strong decrease in median grain size in offshore direction. This region includes the active bar systems and is similar to the inner surf zone classification (region 4) of the present experiments.

Not only the 'equilibrium' distribution of sediments along the coastal profile has been topic of study (see Horn, 1992), also the velocity of the dispersal of sediments is studied, mainly in the investigation of offshore sediment nourishments. Stauble and Cialone (1996) and Stauble and Bass (1999) investigated the distribution of sediments near a beach fill project. The 10-year monitoring comprised recordings of sediment composition at half-year intervals. Their results indicated that the largest change in grain-size distribution occurred in the inner surf zone. Within their time-span of monitoring, Stauble and Bass could study the impacts of some severe winter storms on the dispersal of median sediment sizes. These analyses revealed that the sediments in the inner and outer surf zone become coarser during the storm period. In the subsequent fair weather period, fine sediments from the inner surf zone moved back to the outer surf zone, resulting in a fining of the sediments in the outer surf zone. Sediments in the inner surf zone remained coarse. These observations are consistent with the results of present experiments. A period of increased storm activity resulted again in a coarsening of the entire profile and very coarse material, gravel, was deposited in the outer surf zone at a depth defined as the 10-year average closure depth.

In their paper, Stauble and Bass stress the importance of knowledge on grain-size variations in different sub-environments. Since the distribution of grain size is the result of sediment-transport processes in a specific area, the rate of variations is an indicator of the type of transport processes. Medina *et al.* (1994) showed that changes in cross-shore morphology and sediment composition show a clear seasonal behaviour and are related to the occurrences of storms. The analysis of their data set of sediment composition of a natural coastal profile over several years revealed that morphology will adjust first to hydrodynamic conditions and only then sediment composition will reach steady state. This implies that even when net transport rates are minimal, sediments are still being sorted. This conclusion is in agreement with the present experiments but contradict the results of field measurements by Guillén and Hoekstra (1996). They show that seasonal effects are negligible and that sediment distribution represents an equilibrium in response to a long-term (several years) hydrodynamic regime.

The experiments described in this thesis show that the sediments redistribute fast and the sediment composition can adjust in several hours to changed hydrodynamic conditions. The hydrodynamic conditions during the sampling campaign will therefore determine the measured grain size distribution. The measurements of Guillén and Hoekstra (1996) were made from a ship during conditions that sampling was possible, probably during fair-weather conditions. This can explain the differences in the conclusions between Guillén and Hoekstra (1996) and the work of Stauble and Bass (1999).

In summary, we conclude that *in situ* measuring techniques based on radiometric measurements (see chapter 3) and measurements of friction sound (see chapter 4) are not only comparable to sediment sampling but also yield more detailed and complementary information.

The distributions of median grain size, heavy-mineral concentration and sediment-size classes, show that selective transport processes act differently in varying coastal sub-environments, each characterised by different sediment distributions.

The effects of changing hydrodynamic conditions on sediment distributions on large time scales are topic of debate in literature. Present experiments show that on short time scales these effects are large. In the time-consuming sediment sampling in field conditions, the results can be affected by short-term changes of sediment composition. The new techniques described in this thesis can be used to measure sediment composition fast and *in situ* can improve studies on changes of sediment composition.

Grain-size variations are observed on almost the entire profile. With a low average concentration of heavy minerals, sorting on density occurs mainly in the region just offshore the breaker bar under sheet-flow conditions. To asses these mechanisms and effects on sediment transport in more detail, sediment sorting on density is studied under sheet-flow conditions in a small wave tunnel experiment, described in chapter 7.